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Microcomputed tomographic examination of the osseous structures of the canine carpus

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ABSTRACT

The surgical treatment of carpal joint injuries is associated with a high implant-based complication rate of up to 50 %. For this reason, the aim of the study was to create a database on the bony microarchitecture of the cancellous and cortical structures of the carpus. A total of 80 carpal joints from 20 medium-sized dogs and 20 toy breeds were examined and compared with each other using microcomputed tomography. The parameters bone volume (BV/TV), bone surface (BS/BV), trabecular thickness (Tb.Th), number of trabeculae (Tb.N), trabecular spacing (Tb.Sp), degree of anisotropy (DA) and connectivity density (Conn. D) were measured and compared. In addition, the cortical structure was classified using a three-staged scoring system. It was shown that all carpal bones have a cancellous structure, that differs clearly between the groups, without one group being mechanically superior. The evaluation implies, that the second carpal bone appears to be very stable. The formation of the cortex differs massively between the groups, with the toy breeds having only a very thin, partially interrupted bone lamella, whereas the medium-sized dogs have a normal cortex. Within the toy breed group inhomogeneous results were observed, whereby the values of the Chihuahuas deviated. This breed had significantly fewer (Tb.N) and thinner trabeculae (Tb.Th) with a greater trabecular separation (Tb.Sp), lower bone volume fraction (BV/TV) and higher bone surface (BS/BV). This indicates a decreased stability of the Chihuahua's carpal bones. The results of this study could potentially improve the development of new implants and thus reduce the complication rate.

1. Introduction

Injuries to the carpal joint in dogs are multifaceted, usually consisting of a combination of soft tissue and bone injuries and are often the result of direct trauma (Beierer, 2021). The wide range of potential weak points can be explained by looking at the anatomy of the joint, as it consists of seven individual bones and a number of ligaments, muscles and tendons. The complexity of the joint allows for a wide range of movements (Nickel et al., 2003) but also a large number of potential pathologies (Johnston and Tobias, 2017). Subluxations and dislocations of one or both joint levels have been described, with an increased predisposition to the antebrachiocarpal articulation, hyperextension injuries, fractures of individual carpal bones and a variety of injuries to the ligamentous apparatus are also common (Beierer, 2021; Earley, 1978; Li et al., 2000; Tomlin et al., 2001; Vedrine, 2013). The treatments for these injuries are varied and, depending on the type of injury, consist of a bridging ligament replacement or, in the case of extensive ligament injuries, a complete (panarthrodesis) or partial fusion (partial arthrodesis). In contrast to complete arthrodesis, partial arthrodesis does not involve the antebrachiocarpal articulation in order to maintain the motility of this joint, which accounts for around 70–80 % of the total mobility of the carpus and thus enables a relatively physiological gait (Beierer, 2021; Burton et al., 2013). There are several surgical treatment options for both types of fusions (Bristow et al., 2015; Buote et al., 2009; Burton et al., 2013; Guerrero and Montavon, 2005; Pozzi et al., 2020; Viguier et al., 2001). A screw or pin is inserted into at least one carpal bone (intermedioradial carpal bone +/− ulnar carpal bone) in a ligament replacement, which is usually inserted into the bone with or without an anchor, but also in almost every form of carpal joint arthrodesis. Precise knowledge of the anatomy of the joint and the condition of the bones is therefore important. As there are no detailed studies of the bony structures of the seven different carpal bones in the available literature, the aim of the present study was to investigate the anatomical structures in more detail using microcomputed tomography.

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2. Material and methods

The carpal joints examined in the study came from deceased dogs or dogs which had been euthanised for reasons other than carpal joint disease and were given to the Clinic for Small Animal Surgery and Reproduction at the LMU by the patient owners for scientific purposes. The study was approved by the Ethics Committee of the Faculty of Veterinary Medicine at the LMU (Approval Number: 344–12-12-2022). Care was taken to achieve a balanced ratio of neutered and unneutered animals and only adult animals were included in the study. Diseases that could lead to a reduction in bony integrity, such as chronic renal insufficiency (CNI) or hyperadrenocorticism (HAC), were excluded as far as the preliminary report allowed. For the study, the joints were divided into two groups (Table 1): toy breeds (up to 6.5 kg) and medium-sized dogs (15–35 kg). Both groups consisted of 20 dogs each (40 joints). The carcasses, initially frozen at −20 °C, were thawed at room temperature and the carpi were separated proximally in radius/ulna and distal in the metacarpus. The carpal joint was examined radiographically in 2 planes to rule out pathological bony changes. The soft tissue was then dissected, with exception of the ligaments in the immediate vicinity of the joint, to keep it in its anatomic position. X-ray examinations were performed with the X-ray unit Siemens Luminos dRF, Siemens Healthcare AG (Erlangen), with the settings 50kv/1.6mAs in the toy dogs and 50kv/2mAs in the medium-sized dogs. They were then stored in 4 % formalin until microcomputed tomography examination.

2.1. Microcomputed tomography

The individual carpal joints (n = 80) were fixed vertically in the sample container of the Micro-CT 80 before the scan in order to prevent artefacts caused by rotational movements. The measurement parameters of the micro-computed tomograph used (μCT-80, Scanco Medical, Zurich, Switzerland) were set at 70 kV, 114 μA, an integration time of 550 ms, a native voxel size of 10 μm and 1000 projections/180°. The scan included the intermedioradial carpal bone (Cir), ulnar carpal bone (Cu), accessory carpal bone (Ca), first carpal bone(CI), second carpal bone (CII), third carpal bone (CIII) and fourth carpal bone (CIV) from the proximal to the distal end of the joint. The abbreviated naming of the carpal bones (Cir, Ca, Cu, …) was based on Nickel et al. (2003). The subsequent evaluations were carried out using the μCT evaluation programme V6.6 (Scanco Medical, Zurich, Switzerland).

2.2. Analysis of the trabecular bone of the seven carpal bones

In order to include as much cancellous bone as possible in the analysis, each scan was analysed individually and the most proximal and distal cross-section of the cancellous bone was determined. The trabecular structures within this range were defined as a region of interest (ROI) and then outlined by hand in each individual section on the monitor (Fig. 1), according to Kim et al. (2021). This was done individually for each carpal bone. For each of the two weight groups, a threshold was determined by three independent reviewers and used for the analyses of the structural parameters bone volume fraction (BV/TV (%)), bone surface to volume ration of bone (BS/BV (mm^{-1})), trabecular thickness (Tb.Th (mm)), trabecular number (Tb.N (mm^{-1})), trabecular separation (Tb.Sp (mm)), degree of anisotropy (DA) and connectivity density (Conn. D (mm^{-3})). The Chihuahua was considered separately again within the group of toy breeds, as this breed showed significant deviations in a comparable study by Planner et al. (2021).

Table 1
Layout of both groups including breed and body weight.

Group	Toy breed dogs	Medium sized dogs
Body Weight	2–6.5 kg	15-35 kg
	Chihuahua (n = 5)	Labrador (n = 2)
	Maltese (*n* = 3)	Labrador mix (n = 1)
	Yorkshire Terrier(*n* = 7)	German-Shepherd mix (n = 3)
	Papillon (n = 1)	White Shepherd (n = 1)
	Mini Poodle (n = 1)	Australian Shepherd (n = 1)
	Pomeranian (n = 1)	Border Collie (n = 1)
	Bolonka (n = 1)	Blood Hound (n = 1)
	Deer Pinscher (n = 1)	Schnauzer mix (n = 1)
		Bearded Collie (n = 1)
		Sheepdog (n = 1)
		Mixed breed (n = 7)

2.3. Analysis of the cortical structures

A three-stage scoring system was introduced to categorise the cortical structures (Fig. 2). The scans of all examined carpal joints (n = 80) were evaluated and the cortical bone was assessed for each of the seven bones in the transverse section; for this purpose, each bone was subdivided into a proximal, middle and distal third and the section in the centre was used for evaluation. The intermedioradiale carpal bone was again divided into three parts based on its size: the dorsal surface, the palmar surface and the articulating surface communicating with the ulnar carpal bone. The accessory carpal bone was also subdivided into joint-participating and non-joint-participating. The remaining 5 bones were assessed in their entirety.

2.4. Statistical analysis

Generalised linear models were used to study the differences between group 1 and 2 for every particular carpal bone for following parameters: BS/BV, BV/TV, Conn.D, Corticalis, DA, Tb.N, Tb.Sp and Tb. Th. Furthermore, the Chihuahua was then explicitly compared to the two groups independent of location. The following model assumptions were always checked: (1) the normality of residuals was checked by the Shapiro-Wilk normality test, (2) the homogeneity of variances between groups was checked with Bartlett test, and (3) the heteroscedasticity (constancy of error variance) was checked with Breusch-Pagan test. In case the assumptions were not satisfied, data were log-transformed and linear models were applied again. All contrasts (differences) between particular groups (i.e. toy breeds vs medium sized dogs) were assessed after model-fitting by the estimated marginal means (R package - emmeans) with Tukey p-value correction for multiple comparisons. Results with a P-value <0.05 were considered statistically significant. Data analysis was performed using R 4.2.1 (2022-06-23).

3. Results

All 80 carpal joints examined in both groups were included in the analysis.

The comparison of the right and left sides showed no significant difference for both groups on all seven bones in the trabecular and cortical analyses ($p > 0.58$); the values were almost completely similar, which is why they were not analysed separately.

3.1. Trabecular analysis

All carpal bones of all breeds had a trabecular portion. The results of the measurements for the individual carpal bones and groups are listed in Table 2.

The bone volume percentage (BV/TV) of the toy breeds was only insignificantly higher in 6 of the 7 bones than in the group of medium-sized dogs. Only in the accessory carpal bone it was significantly higher in the toy breeds ($p = 0.001$). Across groups, it was noticeable that the bone volume percentage of the second carpal bone was significantly higher than in the other 6 bones ($p < 0.001$).

The values for the surface volume fraction (BS/BV) of the toy breeds were higher in six of the seven carpal bones than in the medium-sized dogs. This difference was significant in the bones of the proximal joint row (Cir: $p = 0.0325$, Ca: $p = 0.0006$, Cu: $p = 0.0028$). Only in the first

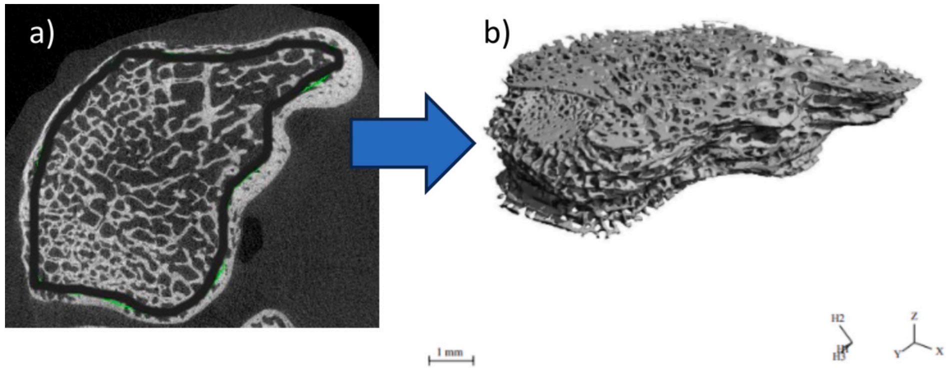

Fig. 1. **a**) Plotted region of interest (ROI) of the trabecular bone at the thickest part of a intermedioradial carpal bone b) 3D reconstruction of the trabecular bone, shown as an example for the intermedioradial carpal bone of a Yorkshire Terrier from group 1.

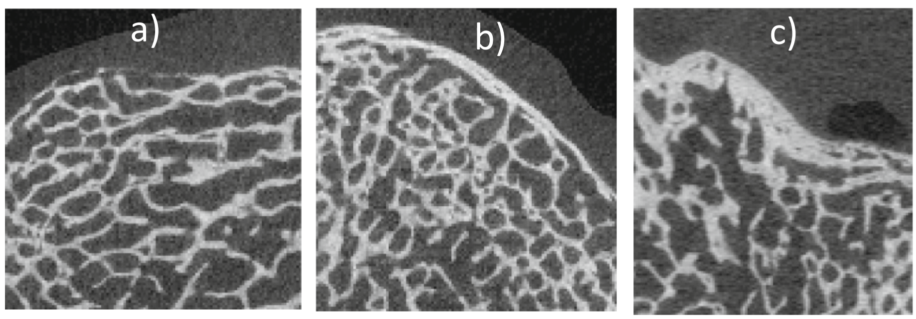

Fig. 2. Scoring system for cortical development a) Score 1: interrupted bone lamella b) Score 2: thin bone lamella c) Score 3: normal bone lamella.

Table 2
Mean value and standard deviation of both groups for all observed parameters at all locations, the group of medium sized dogs (n = 20) is referred to as "Dog", the group of toy breeds (n = 20) as "Toy".

Species	Parameters	Cir	Cu	Ca	CI	CII	CIII	CIV
Dog	BV/TV	0.39 ± 0.07	0.38 ± 0.07	0.36 ± 0.08	0.45 ± 0.08	0.5 ± 0.08	0.4 ± 0.07	0.42 ± 0.08
Toy	(%)	0.4 ± 0.06	0.4 ± 0.06	0.43 ± 0.07	0.46 ± 0.09	0.5 ± 0.08	0.4 ± 0.07	0.43 ± 0.07
Dog	BS/BV	22.25 ± 3.42	23.94 ± 3.59	21.05 ± 4.25	18.83 ± 4.3	18.29 ± 3.68	22.75 ± 3.93	21.15 ± 5.55
Toy	(mm^{-1})	20.37 ± 3.73	21.3 ± 3.58	18 ± 3.09	19.86 ± 4.07	17.81 ± 3.83	21.41 ± 3.92	19.64 ± 3.39
Dog	Tb.N	4.2 ± 0.36	4.45 ± 0.33	3.67 ± 0.33	4.06 ± 0.52	4.48 ± 0.56	4.43 ± 0.6	4.21 ± 0.34
Toy	(mm^{-1})	4 ± 0.34	4.18 ± 0.35	3.76 ± 0.4	4.35 ± 0.41	4.3 ± 0.39	4.11 ± 0.38	4.13 ± 0.43
Dog	Tb.Th	0.09 ± 0.01	0.09 ± 0.01	0.1 ± 0.02	0.11 ± 0.02	0.14 ± 0.16	0.09 ± 0.02	0.1 ± 0.02
Toy	(mm)	0.1 ± 0.02	0.1 ± 0.02	0.11 ± 0.02	0.1 ± 0.02	0.12 ± 0.02	0.1 ± 0.02	0.1 ± 0.02
Dog	Tb.Sp	0.15 ± 0.02	0.14 ± 0.02	0.18 ± 0.03	0.14 ± 0.02	0.11 ± 0.02	0.14 ± 0.02	0.14 ± 0.02
Toy	(mm)	0.15 ± 0.02	0.14 ± 0.02	0.16 ± 0.04	0.13 ± 0.03	0.12 ± 0.03	0.15 ± 0.03	0.14 ± 0.03
Dog	Conn.D	167.85 ± 55.7	167.69 ± 59.71	131.84 ± 46.77	119.5 ± 89.4	140.08 ± 78.91	191.04 ± 98.76	164.57 ± 72.97
Toy	(mm^{-3})	58.11 ± 22.12	60.26 ± 20.75	43.81 ± 15.52	56.95 ± 19.14	57.73 ± 23.13	59.29 ± 21.58	60.33 ± 24.24
Dog	DA	1.15 ± 0.04	1.18 ± 0.05	1.4 ± 0.08	1.34 ± 0.11	1.23 ± 0.07	1.2 ± 0.07	1.35 ± 0.07
Toy		1.27 ± 0.05	1.23 ± 0.04	1.5 ± 0.12	1.44 ± 0.09	1.21 ± 0.06	1.21 ± 0.05	1.35 ± 0.07

carpal bone did the medium-sized dogs show higher values, but without significance ($p = 0.24$). It was noticeable in both groups that the second carpal bone had the lowest values for BS/BV, but without being significant ($p = 0.371$).

The group of toy breeds had significantly fewer trabeculae (Tb.N) in all carpal bones than the group of medium-sized dogs ($p = 0.007$). In addition, the accessory carpal bone of both groups had significantly fewer trabeculae than the other carpal bones ($p < 0.001$) and the second carpal bone had the most trabeculae, but this was not significant ($p = 0.941$).

A comparison of the two groups showed that the group of toy breeds had significantly thicker trabeculae (Tb.Th) on all carpal bones than the group of medium-sized dogs. These differences were most pronounced in the bones of the proximal joint row (Cir: $p = 0.0314$, Cu: $p = 0.0114$, Ca: $p = 0.0007$). Looking at the bones independent of the group, it was also noticeable that the second carpal bone had the thickest trabeculae ($p = 0.05$).

The trabecular distance (Tb.Sp) did not differ significantly between the toy breeds and medium-sized dogs in all carpal bones ($p = 0.615$). However, it was striking that the trabeculae of the accessory carpal bone were significantly further apart in both groups than the other six carpal bones ($p = 0.003$). The second carpal bone had the narrowest trabecular distance across all groups ($p = 0.001$).

The connectivity (Conn.D) was significantly higher in the medium-sized dogs at all seven carpal bones than in the toy breeds ($p < 0.001$). In addition, it was found that the values in the group of toy breeds were quite similar at all localisations, while the medium-sized dogs showed a significantly wider spread of values (Table 2). The lowest values were found in the accessory carpal bone.

The geometric degree of anisotropy (DA) was significantly higher in the toy breed group than in the medium-sized dogs ($p < 0.001$). Again, the differences were most pronounced in the three bones of the proximal joint level (Cir: $p < 0.0001$, Cu: $p = 0.002$, Ca: $p < 0.0001$). The values for the other four bones differed only insignificantly between the groups. Here too, the accessory carpal bone had the significantly highest values in the group-independent comparison of the bones ($p < 0.001$).

3.2. Differences within the groups

Within the group of toy breeds, it was noticeable that the carpal joints of the Chihuahuas differed significantly from the rest of the toy breeds at all carpal bones.

The Chihuahuas had significantly lower values for bone volume percentage (BV/TV) than the other toy breeds ($p < 0.0001$) and also the medium-sized dogs ($p = 0.0005$) (Fig. 3b).

The Chihuahuas showed significantly higher values for surface volume fraction (BS/BV) than the other toy breeds ($p < 0.001$) and also the medium-sized dogs ($p = 0.0243$) (Fig. 3a).

The Chihuahuas had fewer trabeculae (Tb.N) than the other toy breeds or the medium-sized dogs, but only significantly compared to the medium-sized dogs ($p = 0.0051$), not the toys ($p = 0.0862$) (Fig. 3c).

The trabecular distance (Tb.Sp) of the Chihuahuas was significantly higher than in the other toy breeds ($p < 0.0001$) and the medium-sized dogs ($p < 0.0001$), and the Chihuahuas also had significantly thinner trabeculae (Tb.Th) than the other toy breeds ($p < 0.0001$) and the medium-sized dogs ($p = 0.0286$) (Fig. 3d,e).

3.3. Analysis of the cortical structures

In the semi-quantitative evaluation of the cortical development of the individual carpal bones between the two groups, it was noticeable that the cortical bone was very marginally developed in the toy breeds and in some cases consisted only of an interrupted bone lamella (score 1). This was mainly noticeable on the dorsal surface of the intermedioradial carpal bone and on the numbered carpal bones. In the proximal joint row, with the exception of the dorsal surface of the intermedioradial carpal bone, the cortical bone was slightly more developed and consisted of a continuous bone lamella (score 2). In contrast, the cortical bone in the medium-sized dogs was significantly stronger and continuous (score 3). This difference was observed in all seven carpal bones. In both groups, the cortical bone was most pronounced on the palmar surface of the intermedioradial carpal bone, where it was always normal (score 3). The accessory carpal bone also showed a clearly pronounced cortex at the attachment point of the soft tissue structures (score 3). The development of the cortical structures did not differ between the toy breeds, with the Chihuahua showing no special features.

4. Discussion

The exact trabecular and cortical structure of the bones of the canine carpal joint has not yet been described in the available veterinary literature. Knowledge of this is important and could be of significance for the development of implants or the treatment of injuries to these bones. Therefore, the aim of the present study was to close this gap. Healthy dogs were examined for this purpose, and the aim of the work was to gain better knowledge of the anatomical structures and breed differences.

Micro-computed tomography was chosen to analyse the osseous structures of the carpal joint, as it is considered the gold standard for 3-dimensional imaging of bone morphology (Kim et al., 2021; Scherzer et al., 2009). The advantages of this method include the non-destructive examination of the bone and its three-dimensional reconstruction (David et al., 2003; Ito et al., 1998; Müller et al., 1998; Nägele et al., 2004; Scherzer et al., 2009). It has been shown in humans that increased knowledge of the microstructure allows improved prediction of the mechanical competence of the bone (Arlot et al., 2008; Goulet et al., 1994; Pistoia et al., 2002; Ulrich et al., 1997; Ulrich et al., 1999; Van Rietbergen et al., 1998). In this study, the aim was also to utilise the advantages of micro-computed tomography, but not to demonstrate the mechanical superiority of one group over the other.

This knowledge led to microcomputed tomography also being used in veterinary medicine. Most studies have focussed on animals with orthopaedic conditions. Fitzpatrick et al. (2016) investigated the bony changes in dogs suffering from medial coronoid disease (MCD). Scherzer et al. (2009) looked at dogs suffering from Legg-Calve-Perthes and the resulting changes in the femoral head. Boyd et al. (2005) investigated the bony changes in the proximal tibia after rupture of the cranial cruciate ligament in cats in a long-term comparison. These studies showed that the trabecular structure of the bone changes during pathological processes. The trabecular structure of the antebrachium in toy dogs and small dogs was compared by Planner et al. (2021) to investigate the increased predisposition of antebrachial fractures in toy breeds. The authors only examined healthy dogs, which is why a comparison with our own study is possible; clear differences between the two groups were also found here and the separate position of the Chihuahua could also be reproduced. In another study, the first and second lumbar vertebrae of spayed female dogs were analysed to investigate whether female dogs are also potentially susceptible to osteoporosis after spaying (Kostenko et al., 2023). However, due to the small study population ($n = 5$), no meaningful data could be obtained and further investigations are necessary. These studies show that there is also great interest in this examination method in dogs with regard to the quality and changes in the bone. Our own study also showed clear differences between the groups. This shows clearly that in addition to the already complex anatomy of the carpal joint, the differences in cortical and trabecular bone structure and breed differences must also be taken into account in the surgical treatment of carpal joint trauma.

In human medicine, there are studies that have investigated the changes in the trabecular structure of the carpal joint in order to gain a better understanding of osteoarthritis in the thumb saddle joint (Lee et al., 2013; Nufer et al., 2008). The authors investigated the Os trapezium, which corresponds to the first carpal bone in dogs. In humans, this communicates with the thumb and therefore experiences a completely different load than in dogs. It should also be noted that, unlike humans, dogs need their carpus to walk and that it is loaded with 30 % of the body weight during exercise (Budsberg et al., 1987). Lee et al. (2013) were able to show in humans that the structural parameters within a bone differ according to the force applied. The structural parameters BV/TV and Tb.N were highest at sites with high mechanical stress. If this assumption is transferred to the present study, it is noticeable that it is not the intermedioradial carpal bone as the largest carpal bone, as assumed, but the underlying second carpal bone that has the highest values for BV/TV and Tb.N. This suggests that in dogs the force transmission of the intermedioradial carpal bone is concentrated on the second carpal bone.

The bone volume fraction (BV/TV) can strongly influence the mechanical properties of cancellous bone and can be used as one of the primary determinants for the failure load of bone (Ding et al., 2002; Pothuaud et al., 2002). It also correlates with other structural parameters such as trabecular number (Tb.N), trabecular thickness (Tb.Th) and connectivity (CONN·D) (Goulet et al., 1994; Hildebrand et al., 1999). According to Arlot et al. (2008) bony microdamage is associated with low values for BV/TV. In the present study, the values of toy breeds and medium-sized dogs differed only slightly. Kang et al. (2016) were able to show in their study that high values for BV/TV are good determinants for the primary stability of implants.

The surface volume fraction (BV/BV) describes the ratio of the trabecular surface to the volume of the trabecular bone (Goulet et al., 1994). This value is dependent on the number of trabeculae and correlates negatively with the BV/TV (Scherzer et al., 2009). It follows that low values indicate a more compact structure and thus increased

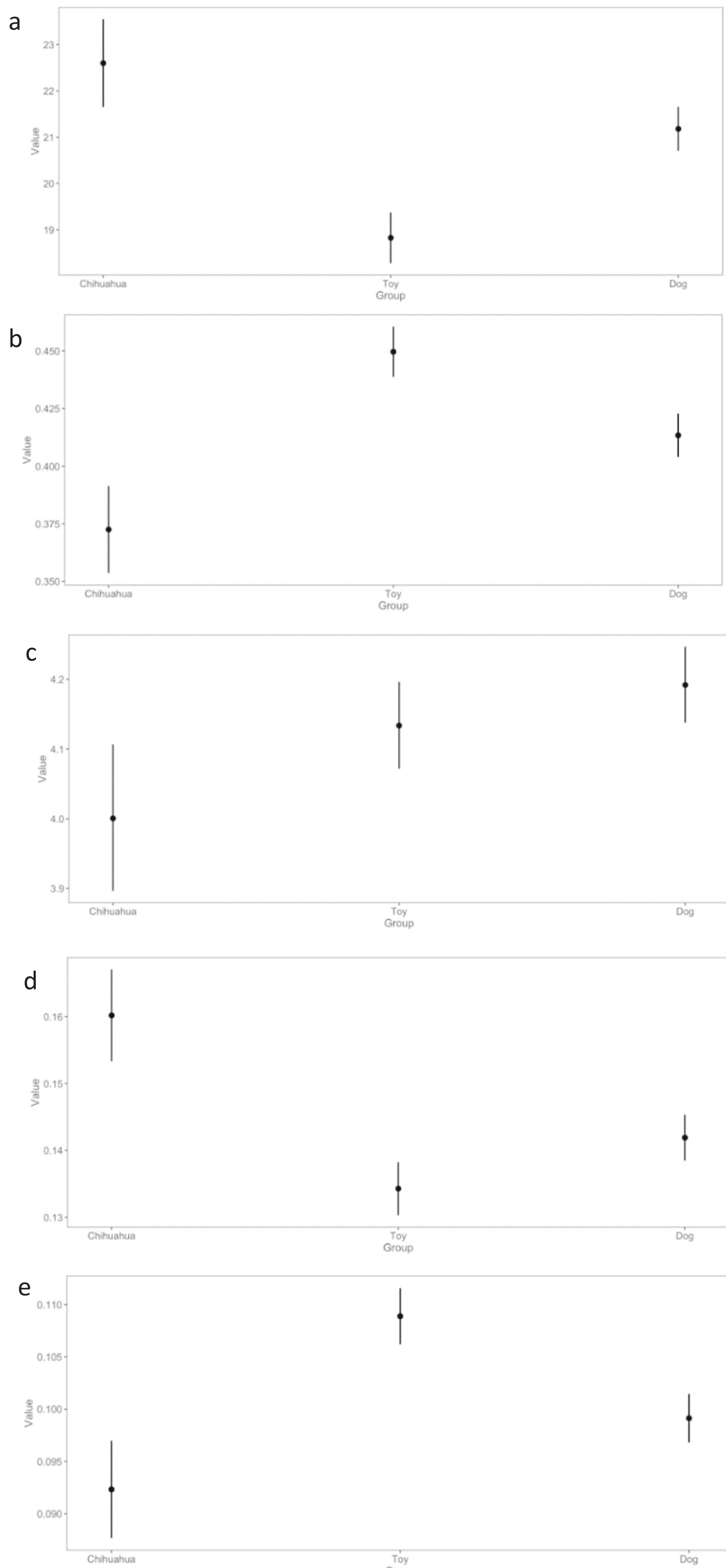

Fig. 3. Comparison between the Chihuahuas ($n = 5$), the toy dogs of other breeds (Toy Group, $n = 15$) and the group of medium-sized dogs (Dog, $n = 20$) for the parameters BS/BV (a), BV/TV (b), Tb.N (c), Tb.Sp (d) and Tb.Th (e).

stability of the bone. In the present study, the toy breeds had significantly lower values than the medium-sized dogs. The fact that the second carpal bone also had the lowest values in both groups supports the hypothesis that it is particularly stable.

Looking at the number of trabeculae, the trabecular thickness and the trabecular spacing, these are also strongly correlated with the stability of the bones. A low number and thickness, as well as wide spacing, are considered negative for bone stability and the primary retention force of implants (Arlot et al., 2008; Boyd et al., 2005; Ito et al., 1998; Kang et al., 2016). In the present study, the medium-sized dogs had significantly more trabeculae in each bone than the toy dogs, but these were significantly thinner. The distance between the trabeculae did not show any major difference between the two groups. The second carpal bone also had the highest values for trabecular thickness and trabecular number and the lowest values for trabecular distance of all seven bones. This also speaks in favour of the increased stability of this bone.

The degree of connectivity of the trabecular bone (Conn.D) makes it possible to make a statement about the quantity of trabecular connections, but not about the quality (Goulet et al., 1994). Furthermore, connectivity is negatively related to the mechanical failure load of the bone (Ding et al., 2002). In our own study, the medium-sized dogs had significantly higher values for Conn.D on all bones than the toy breeds. In addition, the medium-sized dogs showed a much higher dispersion of values compared to the toy breeds. This can be explained by the fact that the weight difference between the individual dogs in this group was significantly greater than in the toy breed group.

The spatial orientation of the trabeculae within the bone is referred to as the degree of anisotropy (DA). High values have a negative influence on the mechanical properties and fragility of the bone (Ding et al., 2002; van Eijden et al., 2006). In our own study, the toy breeds presented significantly higher values compared to the group of medium-sized dogs. Looking at the lower values of the toy breeds for the degree of cross-linking (Conn.D) and the higher values for the degree of anisotropy (DA), it is noticeable that the trabeculae of the toy breeds have fewer cross-links and are arranged more in one direction, which suggests a lack of formative stimulation of the bones due to less strain.

The accessory carpal bone should be considered separately again, as it is an apophysis that is orientated towards tensile loads and therefore has a different function in the carpal joint than the other 6 bones (Evans and de Lahunta, 2012). Compared to the other bones, it has the lowest number of trabeculae with the widest spacing, and they also have fewer branches than the trabeculae of the other bones (Conn.D). This can be explained by the fact that it participates only slightly in the transmission of force along the longitudinal axis of the thoracic limb and therefore does not have to be equally stable in all directions. In this context, however, it is striking that it has the highest degree of anisotropy, which means that the trabeculae are predominantly arranged in one direction in order to best withstand the tensile loads.

The thickness of the cortex did not differ within a bone in our own study. This applied to all bones in both groups. However, there was a clear difference between the groups. The medium-sized dog group had a significantly thicker cortex than the toy breed group. In the toy breed group, the cortex was very weakly developed on all bones and in some cases consisted only of an interrupted bone lamella. According to various studies, the development of the cortical bone has a major influence on the stability and failure load of bones (Eckstein et al., 2004; Lochmüller et al., 2002; Lochmüller et al., 2008). In particular, the thickness is also of importance for the stability (Fonseca et al., 2014) and the retention force of implants (Seebeck et al., 2005). Since the characteristics differ so greatly between the groups, it can be assumed that the higher weight, the associated higher load and also the increased agility in larger dogs have a significant influence on the characteristics. It should again be emphasised that the accessory carpal bone has a strongly developed cortex at the attachment area of the soft tissue structures in order to provide sufficient attachment surface and also to be able to withstand the tensile forces. The reason for the strongly developed cortex on the palmar surface of the intermedioradial carpal bone is probably caused by the increased load from the neighbouring tendons of the long digit muscles.

Among the toy breeds in our study, the Chihuahua was the breed that stood out. The Chihuahua differed from the other toy breeds in five of the seven measured structural parameters on all seven carpal bones. In addition to a reduced BV/TV and increased BS/BV, this breed had fewer, thinner trabeculae with wider spacing. This indicates a reduced stability of the carpal bones of this breed compared to the rest of the group. In their study Planner et al. (2021), were also able to demonstrate altered parameters for the Chihuahua compared to other small dogs and toy breeds. Why the Chihuahua exhibits these peculiarities could not be clarified in this study. It can be speculated that the Chihuahua, which is listed by the FCI as the smallest dog breed in the world, has acquired these abnormalities because it is often carried by its owners and the formative stimulus acting on the bones is therefore low.

Surgical treatment of carpal joint injuries, especially fusion, is associated with increased complication rates of up to 50 % (Arnott et al., 2008; Michal et al., 2003). Most of these complications occur due to the implants used (Buote et al., 2009). The present study shows that the bony architecture of dogs of different sizes does differ. In addition to the above-mentioned importance of the cortical bone on the holding force of implants, the trabecular network also has an influence (Wirth et al., 2011). Here, the stability of the implants depends on the contact surface to the trabecular bone, which is usually quite small (Joffre et al., 2017). As a result, extremely precise selection of the implants used is required (Chapman et al., 1996). The data from the present study show that all 7 carpal bones have a cancellous structure and can therefore potentially be included in a fusion. The second carpal bone, which appears to be particularly stable, could be included in a joint fusion in order to have an additional screw in the distal joint row and thus achieve a more rigid fixation. At present, there is only one study investigating the use of an implant that includes the ulnar carpal bone in addition to the intermedioradial carpal bone (Burton et al., 2013). In this study, it was shown that this reduces intercarpal and carpometacarpal micromovements and enables a more distal positioning of the plate, which means a lower risk of soft tissue impingement. Further possibilities should be evaluated in future studies.

A primary limitation of the present study is the partial lack of age of the animals. Age-related influences were found for the number of trabeculae and trabecular thickness (Bergot et al., 1988). In our studies, animals were examined whose age was between 8 and 12 years in order to minimise age-related influences. The age range is due to the fact that only euthanised or deceased animals were included for animal welfare reasons.

5. Summary

In this study, trabecular structural parameters and the cortical architecture of the seven carpal bones were analysed using micro-computed tomography to evaluate the anatomy and possible differences between toy breeds and medium-sized dogs, as well as within the toy breed group. It was shown that all carpal bones, no matter how small, have the classic cancellous structure and can therefore potentially be used for the surgical treatment of carpal joint trauma. The second carpal bone in particular should be investigated in further studies, as it appears to be very stable. With an additional fixation option, the complication rate of joint fusion could be reduced. It could also be shown that the Chihuahua differs significantly from the other toy breeds and that there is definitely reduced stability here.

6. Explanations

The manuscript of this study was written by LG with contributions from all co-authors. The authors had no conflict of interest, and this research was not financially supported.

CRediT authorship contribution statement

L. Goldstein: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **A.-C. Waselau:** Writing – review & editing, Validation, Supervision, Resources. **Y. Zablotski:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis. **A. Meyer-Lindenberg:** Writing – review & editing, Validation, Resources, Project administration.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL in order to translate the original draft of the paper from German into English. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no conflict of interest. The research was not financially supported.

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